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Optimizing Reliability using BECAS - an Open-Source Cross Section Analysis Tool

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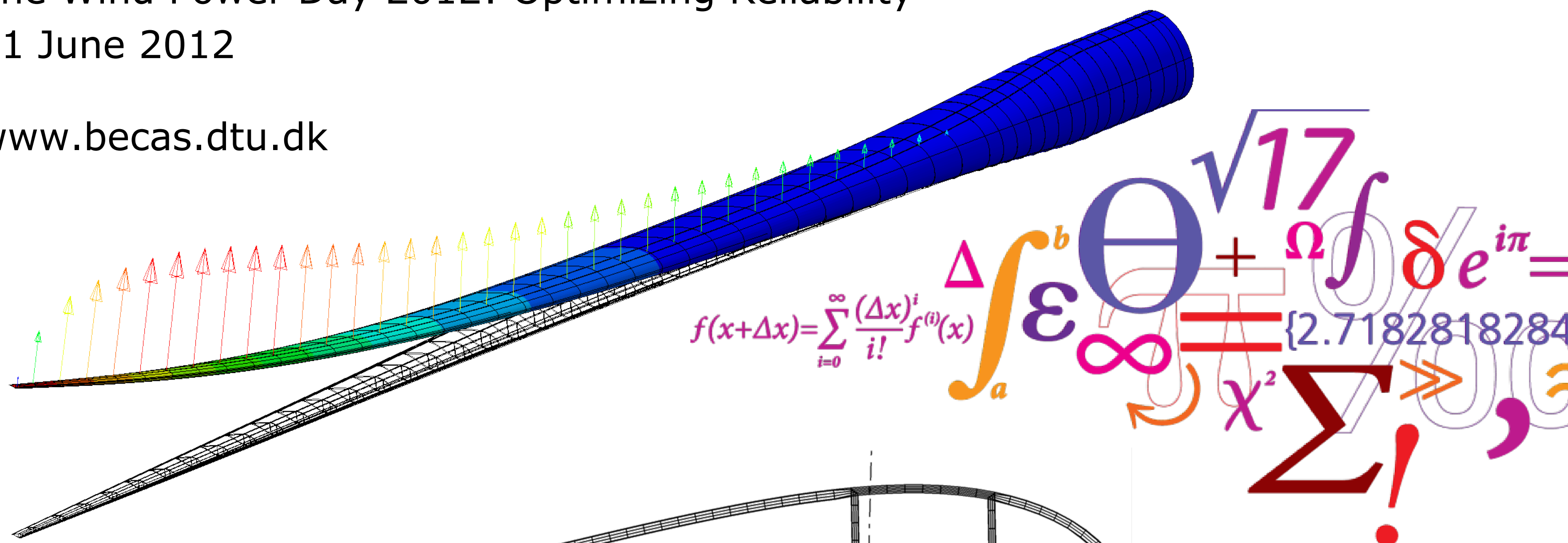

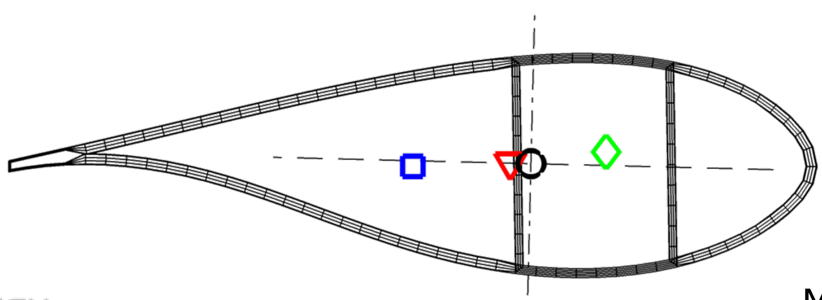

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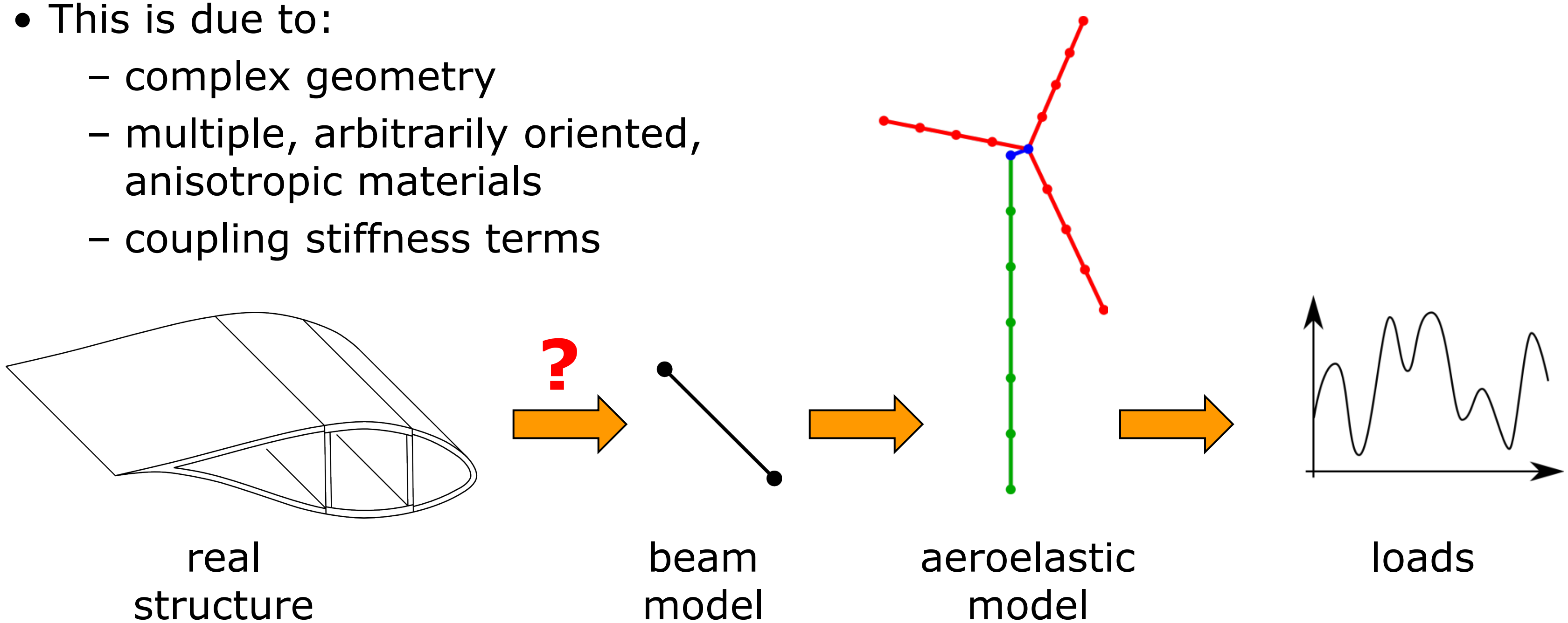
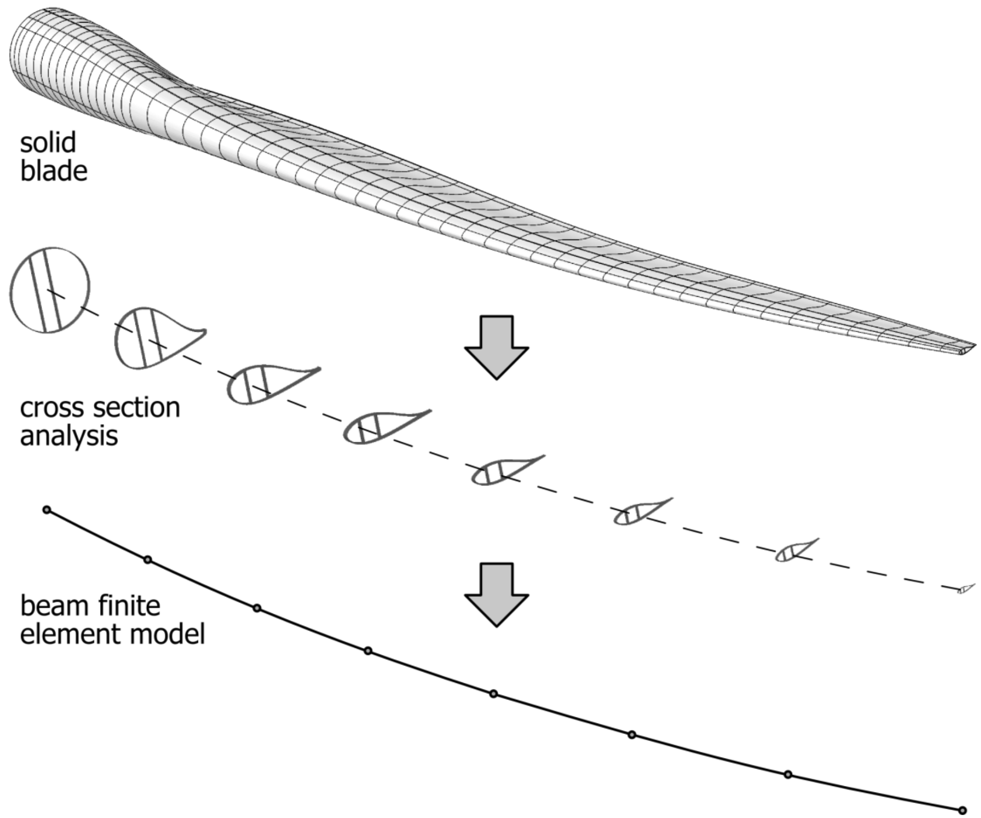
Optimizing Reliability

- Many components of a wind turbine are designed based on loads that are derived using an aeroelastic model of the turbine (e.g. HAWC2).
- Underestimating the real loads will lead to premature failure!
- The aeroelastic model usually relies on beam theory to describe various parts of the turbine.
- In case of the blades, determining the parameters of the beam model proves difficult.
- This is due to:
  - complex geometry
  - multiple, arbitrarily oriented, anisotropic materials
  - coupling stiffness terms



BECAS - an Open-Source Cross Section Analysis Tool

- BECAS is a general purpose cross section analysis tool.
- BECAS determines the stiffness and mass properties of an arbitrary beam cross section, while accounting for all the geometrical and material induced couplings.
- BECAS is based on the theory originally presented by Giavotto et al.[(1)]
- BECAS was developed by José Pedro Blasques (DTU Wind Energy) and Boyan Lazarov (DTU Mechanical Engineering).

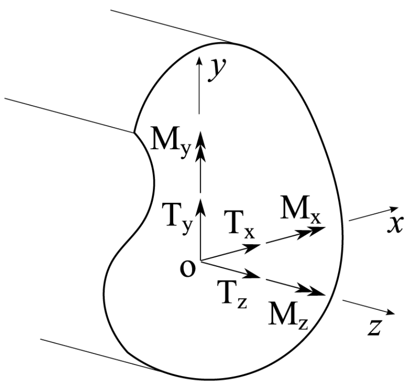


Theory

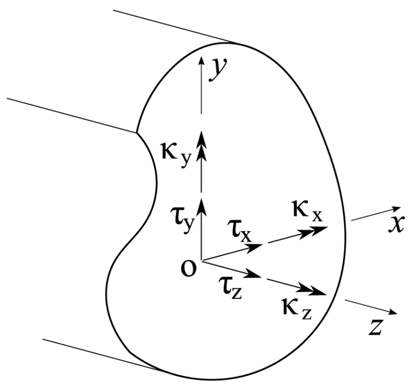
For a linear elastic beam there exists a linear relation between the vector of cross section forces and moments $\boldsymbol{\theta}$, and the resulting strains and curvatures $\boldsymbol{\psi}$:

$$\boldsymbol{\theta} = \mathbf{K}\boldsymbol{\psi}$$

$$\begin{bmatrix} T_x \\ T_y \\ T_z \\ M_x \\ M_y \\ M_z \end{bmatrix} = \begin{bmatrix} K_{11} & K_{12} & K_{13} & K_{14} & K_{15} & K_{16} \\ K_{21} & K_{22} & K_{23} & K_{24} & K_{25} & K_{26} \\ K_{31} & K_{32} & K_{33} & K_{34} & K_{35} & K_{36} \\ K_{41} & K_{42} & K_{43} & K_{44} & K_{45} & K_{46} \\ K_{51} & K_{52} & K_{53} & K_{54} & K_{55} & K_{56} \\ K_{61} & K_{62} & K_{63} & K_{64} & K_{65} & K_{66} \end{bmatrix} \begin{bmatrix} \tau_x \\ \tau_y \\ \tau_z \\ \kappa_x \\ \kappa_y \\ \kappa_z \end{bmatrix}$$



(a) Forces and moments



(b) Strains and curvatures

This cross section stiffness matrix is what BECAS computes!

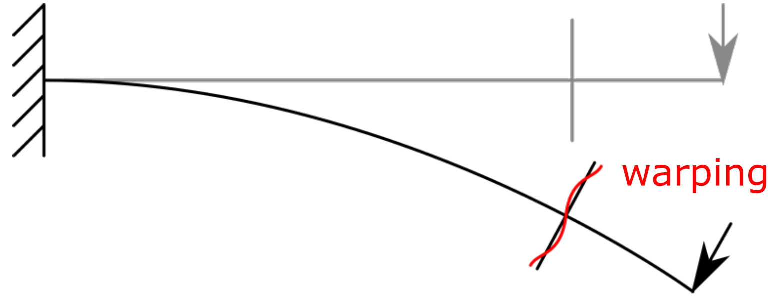
Theory

$$
\begin{array}{rc}
 & \begin{array}{cccccc} \text{shear\_x} & \text{shear\_y} & \text{extension} & \text{bending\_x} & \text{bending\_y} & \text{torsion} \end{array} \\
\begin{array}{r} \text{shear\_x} \\ \text{shear\_y} \\ \text{extension} \\ \text{bending\_x} \\ \text{bending\_y} \\ \text{torsion} \end{array} &
\begin{bmatrix}
K_{11} & K_{12} & K_{13} & K_{14} & K_{15} & K_{16} \\
 & K_{22} & K_{23} & K_{24} & K_{25} & K_{26} \\
 & & K_{33} & K_{34} & K_{35} & K_{36} \\
 & & & K_{44} & K_{45} & K_{46} \\
 & \underline{\text{(sym.)}} & & & K_{55} & K_{56} \\
 & & & & & K_{66}
\end{bmatrix}
\end{array}
$$

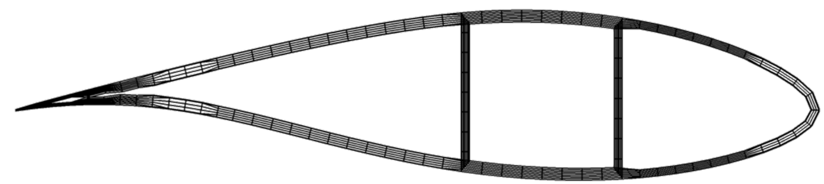
- shear stiffness x-direction
- shear stiffness y-direction
- extensional stiffness
- bending stiffness about x-axis
- bending stiffness about y-axis
- torsional stiffness

Theory

- It is assumed that the cross section deformation is defined by a superimposition of the rigid body motions and warping deformations.
- The cross section is discretized using two dimensional finite elements to interpolate the 3D warping deformations.
- Application of the principle of virtual work yields the finite element form of the cross section equilibrium equations.
- These equations allow to determine the resulting vector of strains and curvatures for a given vector of cross section forces and moments.
- If 6 vectors of strains and curvatures are determined for 6 ”unit loads”, the 6x6 cross section stiffness matrix K can be determined.



2D finite element mesh



cross section equilibrium equations

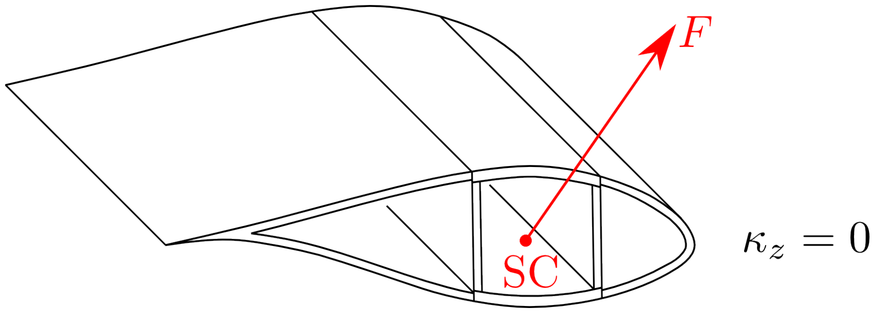
$$\left\{\begin{array}{l}\mathbf{E}\frac{\partial \mathbf{u}}{\partial z}+\mathbf{R}\frac{\partial \boldsymbol{\psi}}{\partial z}=0\\ \mathbf{R}^T\frac{\partial \mathbf{u}}{\partial z}+\mathbf{A}\frac{\partial \boldsymbol{\psi}}{\partial z}=\frac{\partial \boldsymbol{\theta}}{\partial z}\end{array}\right.$$

$$\left\{\begin{array}{l}\mathbf{E}\mathbf{u}+\mathbf{R}\boldsymbol{\psi}=\left(\mathbf{C}-\mathbf{C}^T\right)\frac{\partial \mathbf{u}}{\partial z}+\mathbf{L}\frac{\partial \boldsymbol{\psi}}{\partial z}\\ \mathbf{R}^T\mathbf{u}+\mathbf{A}\boldsymbol{\psi}=-\mathbf{L}^T\frac{\partial \mathbf{u}}{\partial z}+\boldsymbol{\theta}\end{array}\right.$$

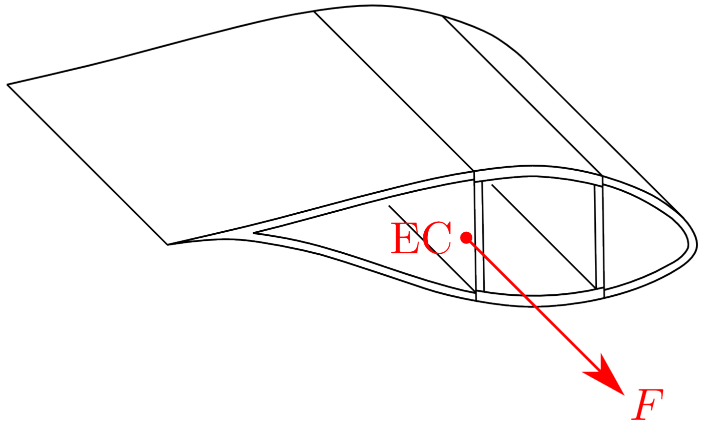
Theory

- From the cross section stiffness matrix the location of various centers can be computed.

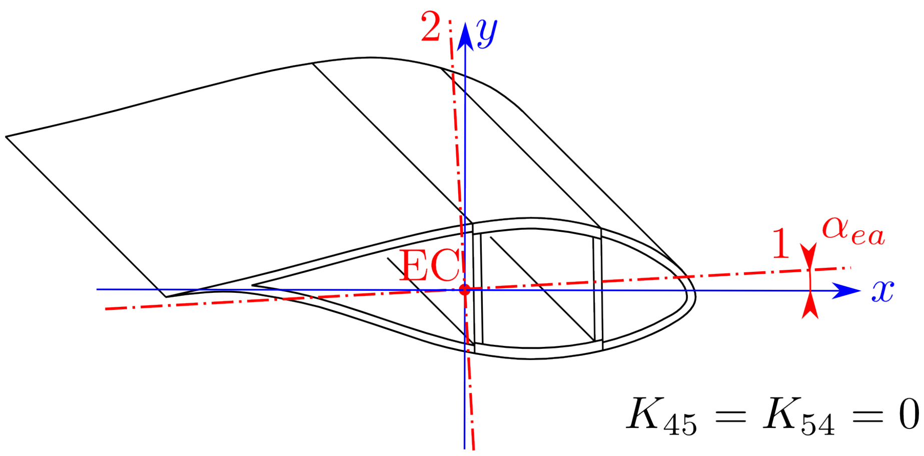
shear center



elastic center

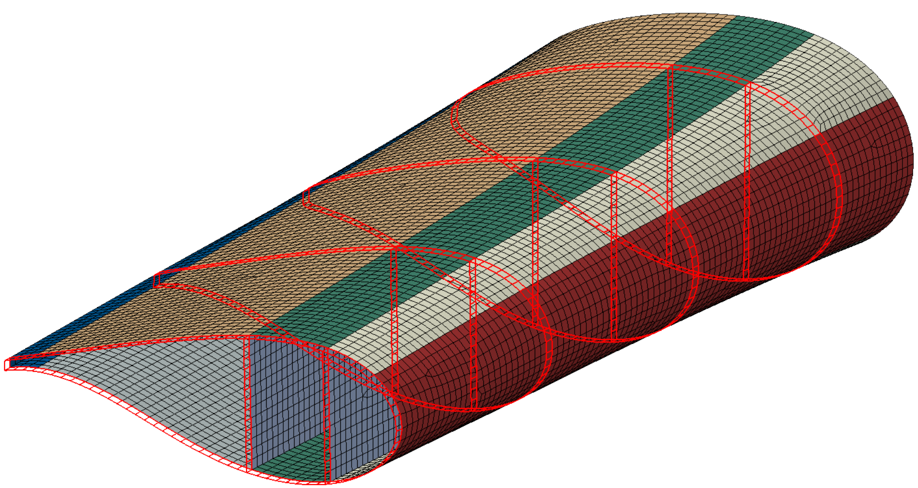


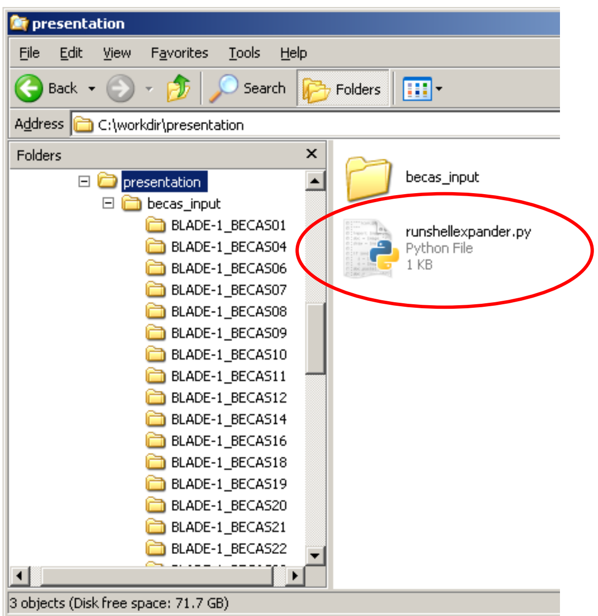
elastic axes orientation



Example: Analysis of a Wind Turbine Blade

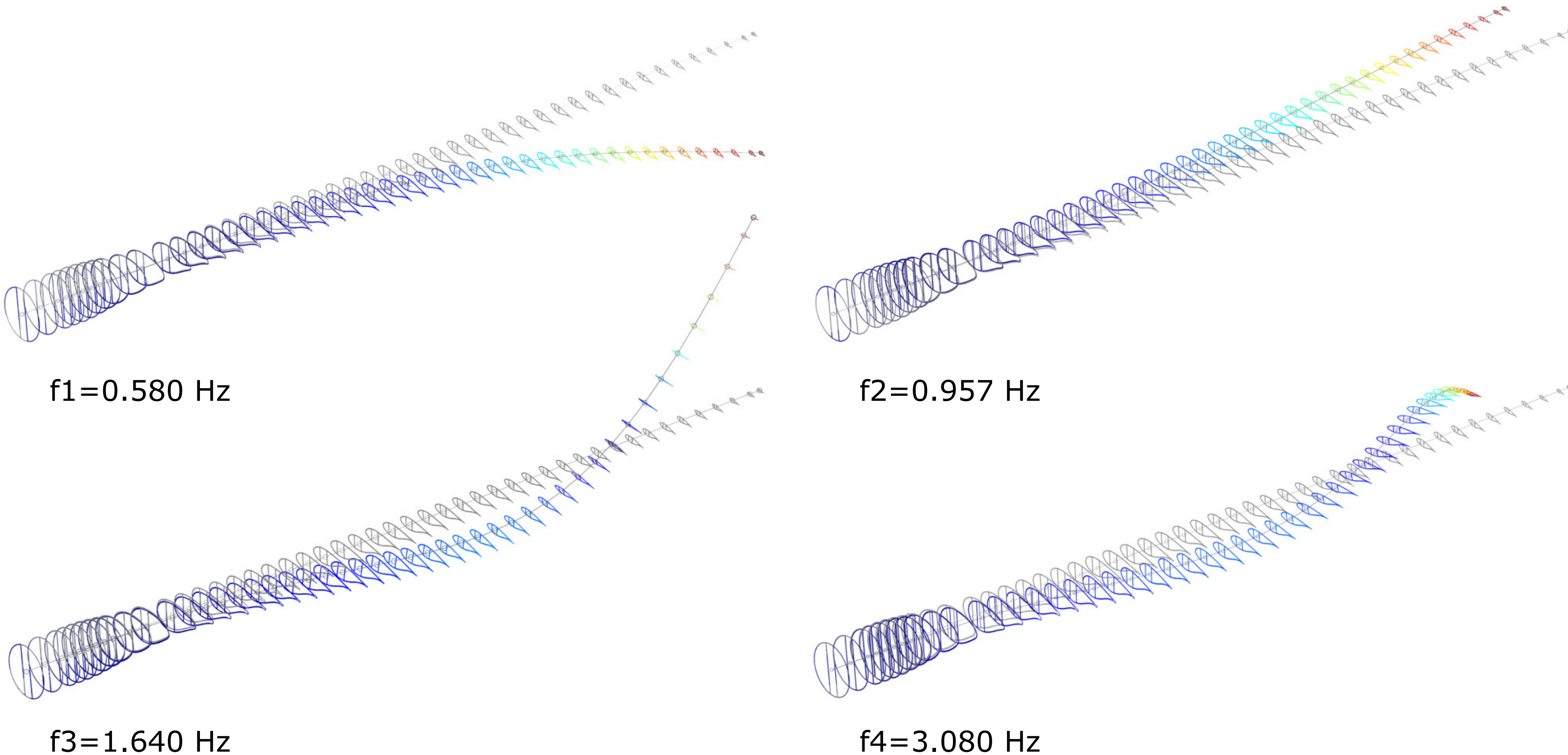
finite element shell model → shellexpander (python program) → BECAS input files → **BECAS** → cross section stiffness matrices → finite element beam model





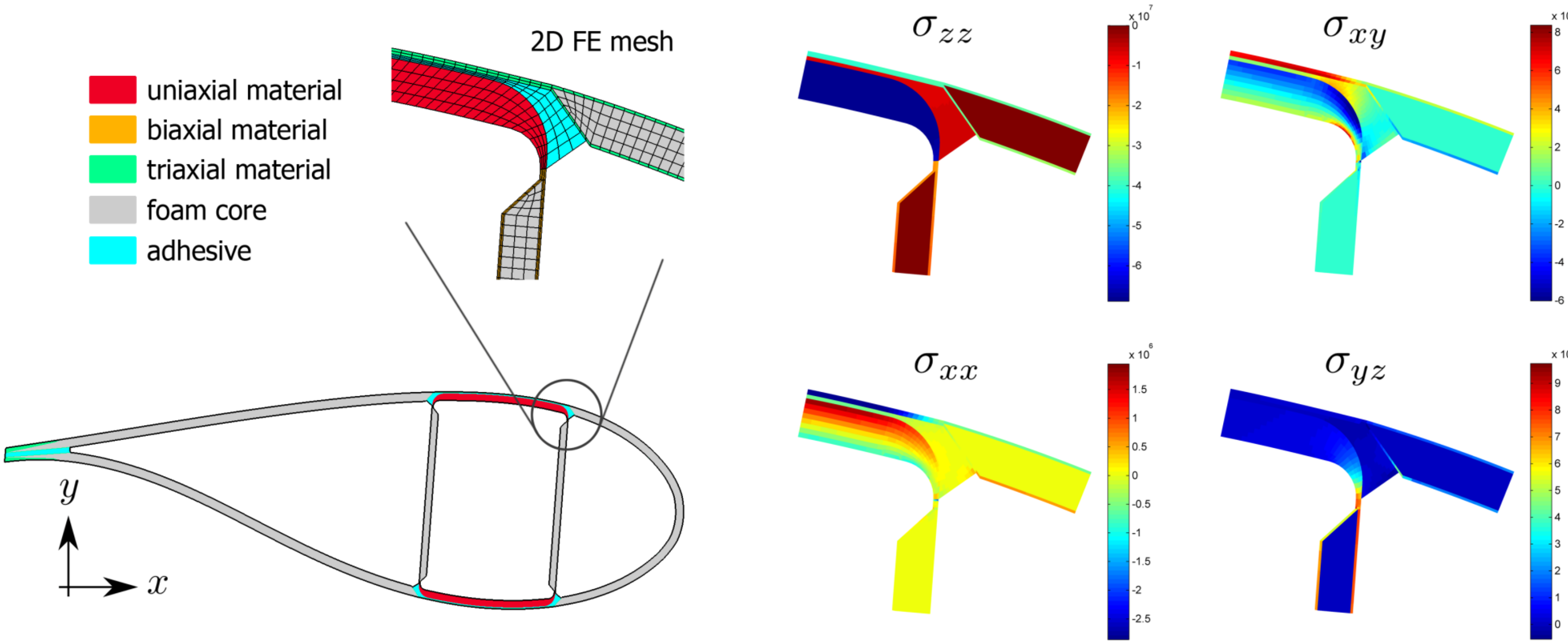
Example: Analysis of a Wind Turbine Blade

- Eigenfrequencies obtained from the BECAS-based beam model match the results from the original finite element shell model.



Outlook: Stress Recovery

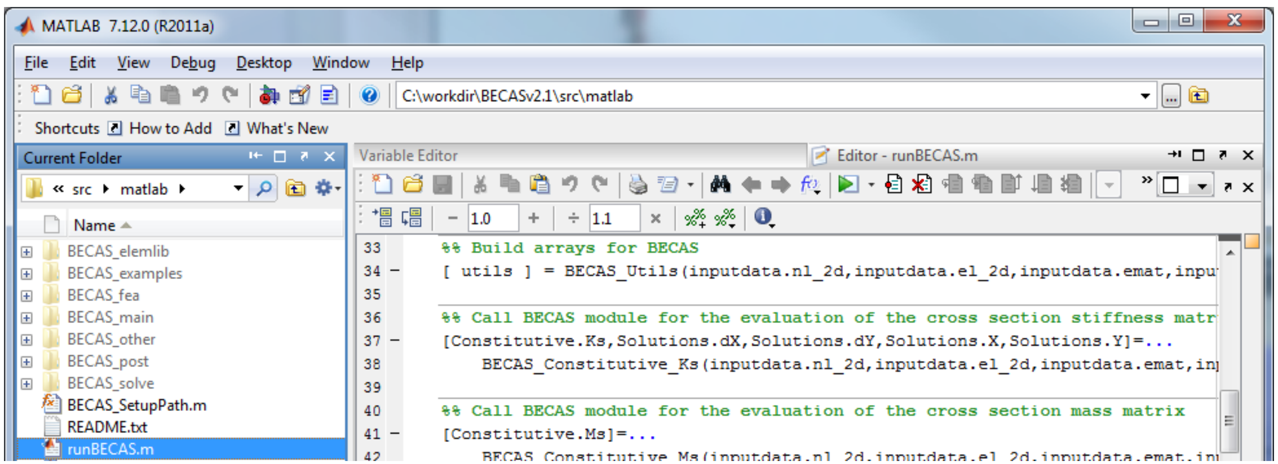
- The cross section forces and moments coming from a beam model can be used to compute the local 3D stresses for each cross section.



- In the process of being validated.
- Will be part of a future release of BECAS.

Why choose BECAS?

- Many other cross section analysis tools are available – why choose BECAS?
  - BECAS is open source! It is distributed as Matlab® source code.
  - Alternatively it is available as a compiled version, which does not require a Matlab license.
  - The BECAS license is free of charge for academic use.
  - BECAS has been validated extensively and comes with a comprehensive user's manual.
  - BECAS is fast, when used with the free SuiteSparse package.
  - Integrated with HAWC2



Thank you.

Further information?

BECAS Webpage: www.becas.dtu.dk

Mail: BECAS-DTUWind@dtu.dk

Literature

(1) Giavotto V., Borri M., Mantegazza P., Ghiringhelli G., Carmaschi V., Maffiolu G.C., Mussi F., *Anisotropic beam theory and applications*, Composite Structures, (16)1-4, 403-413, 1983

(2) Blasques J. P., *User's Manual for BECAS v2.0 - A cross section analysis tool for anisotropic and inhomogeneous beam sections of arbitrary geometry*, DTU-RISØ, Technical Report RISØ-R 1785, 2011

(3) Blasques J. P., Stolpe M., *Multi-material topology optimization of laminated composite beam cross sections*, Composite Structures, Available online 10 May 2012, http://dx.doi.org/10.1016/j.compstruct.2012.05.002.